SMEFT at NLO for the Drell-Yan Process

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In Search of New Physics Using SMEFT
Argonne National Laboratory

1808.05948, with S. Dawson
1811.12660, with S. Dawson and P.P. Giardino

Using SM processes to limit general NP

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \sum \frac{C_i}{\Lambda^2} \mathcal{O}_i$$

B, L conservation, MFV → 59 independent dim. 6 operators

Higher dimension operators grow with energy

Look for interference with SM

LHC is already competitive

EFT and the LHC

Indirectly probe new physics, e.g. SMEFT

$$\mathcal{L} \supset g_{\mathrm{SM}}\mathcal{O}_{\mathrm{SM}} + \frac{g_{\mathrm{BSM}}}{\Lambda^2}\mathcal{O}_{\mathrm{BSM}}$$

Standard story: effect of higher dimension operators grows with energy

$$\mathcal{M} \sim g_{\mathrm{SM}} + g_{\mathrm{BSM}} s/\Lambda^2$$

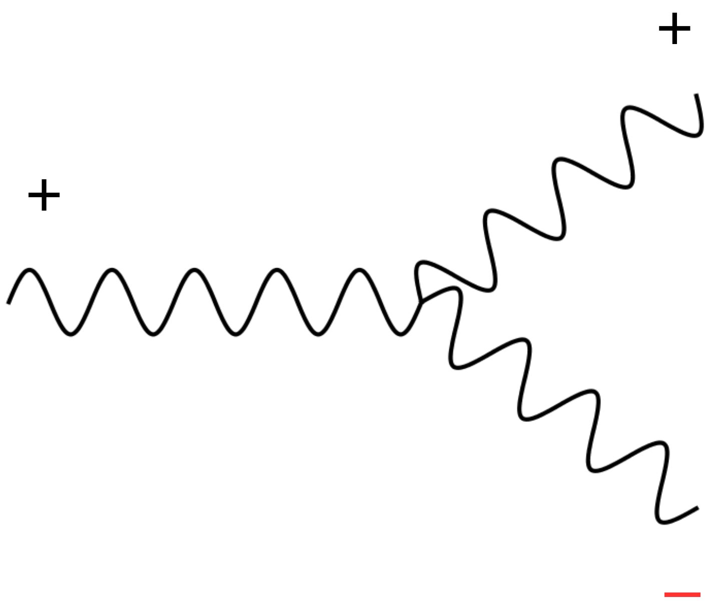
Interference is dominant contribution

$$|\mathcal{M}|^2 \sim g_{\mathrm{SM}}^2 + \frac{g_{\mathrm{SM}} g_{\mathrm{BSM}} s}{\Lambda^2} + \mathcal{O}(\Lambda^{-4})$$

Look for large effects in tails of distributions

Interference and the SMEFT

What if SM and BSM amplitudes do not interfere?

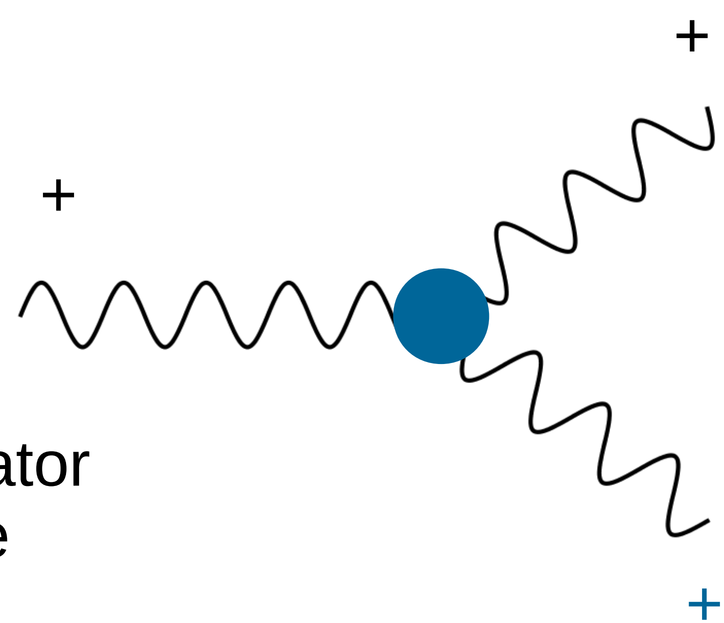


e.g. transverse gauge bosons

all particles outgoing
ignoring masses

different helicity structures

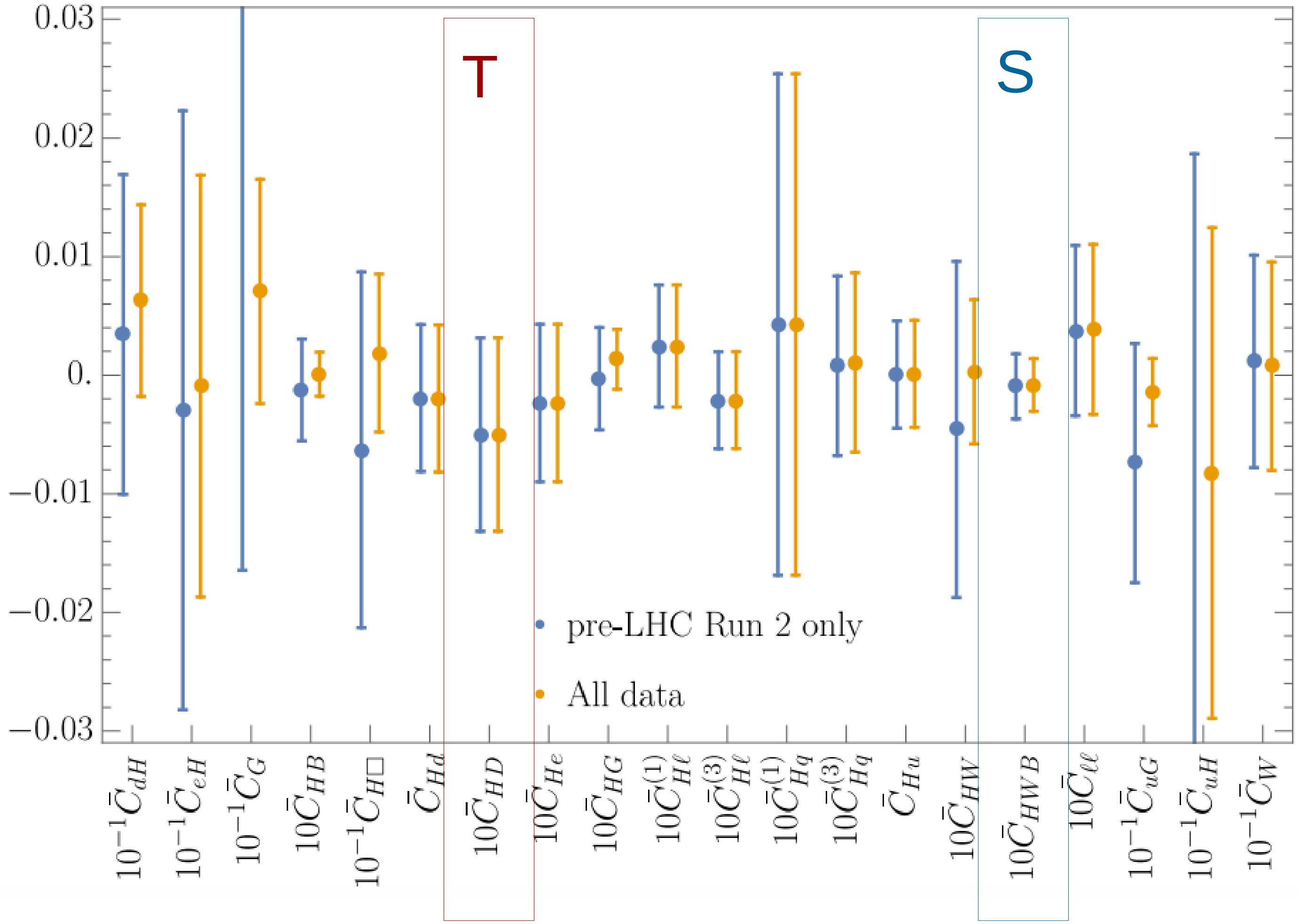
$$\mathcal{O}_W = \epsilon_{abc} W_\mu^{\nu a} W_\nu^{\rho b} W_\rho^{\mu c}$$



actually true for *any* dimension 6 operator
contributing to the 3-point amplitude

Global SMEFT fits

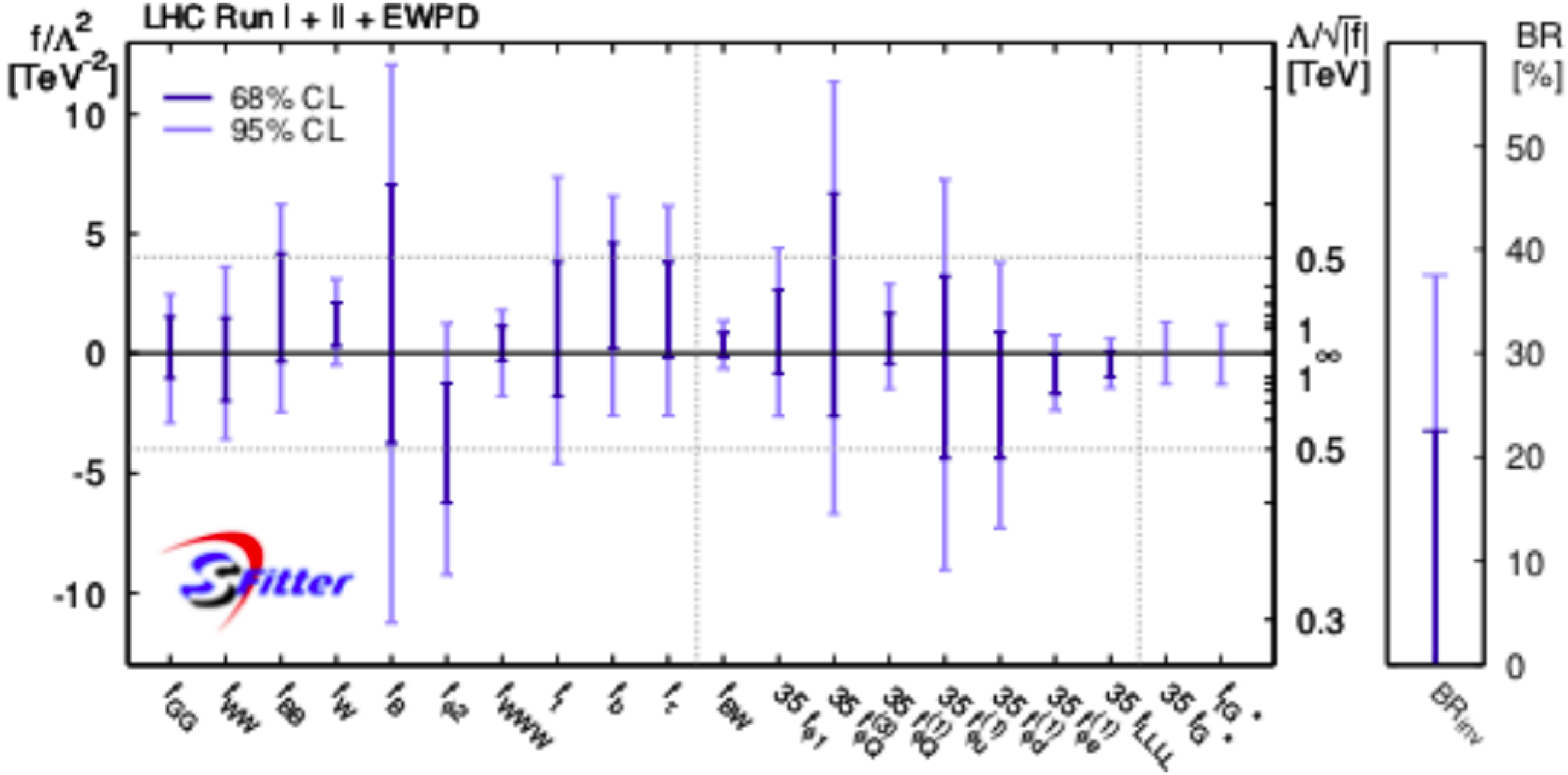
Fit to EWPO, LHC diboson and Higgs data shows where LHC bounds already compete with those from LEP



Ellis, Murphy, Sanz, You 1803.03252

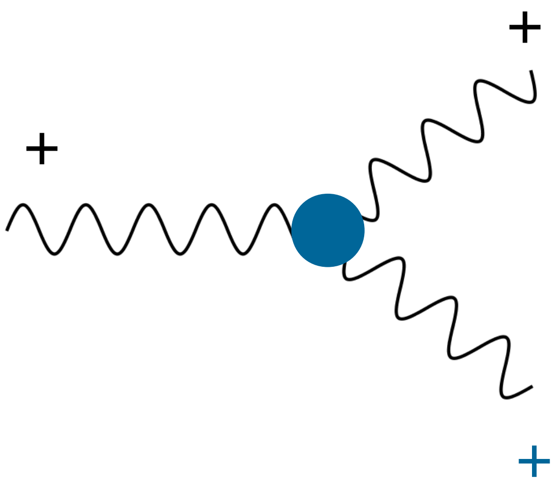
Global SMEFT fits

Consistent global fit at one loop will require NLO calculations in SMEFT



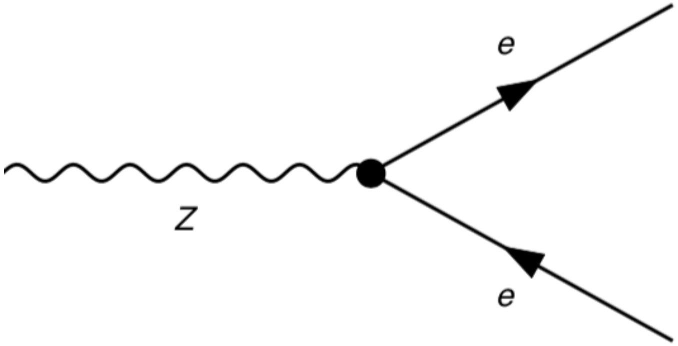
Biekotter, Corbett, Plehn
1812.07587

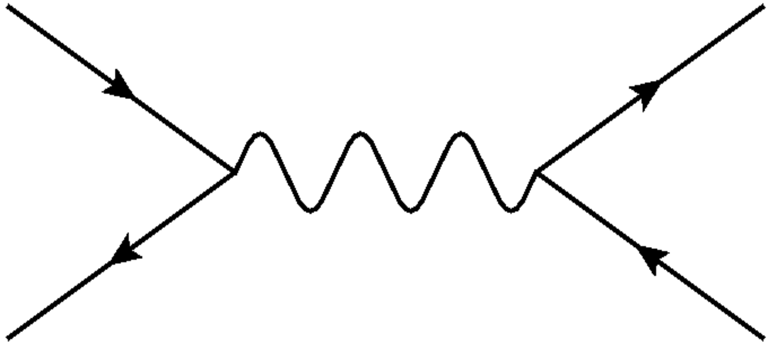
Plan



SMEFT interference and its restoration at NLO

Z boson decay





Drell-Yan

Interference suppression

SM and BSM give different helicities for any 2 → 2 process involving a transverse V

Channel	SM	BSM$_6$
$++++$	ε_V^4	ε_V^0
$+++-$	ε_V^2	ε_V^0
$++--$	ε_V^0	ε_V^2
$+\frac{1}{2}-\frac{1}{2}++$	ε_V^2	ε_V^0
$+\frac{1}{2}-\frac{1}{2}+-$	ε_V^0	ε_V^2
$+\frac{1}{2}-\frac{1}{2}\,0+$	ε_V^1	ε_V^1
$+\frac{1}{2}-\frac{1}{2}\,0\,0$	ε_V^0	ε_V^0

Channel	SM	BSM$_6$
$0+++$	ε_V^3	ε_V^1
$0++-$	ε_V^1	ε_V^1
$0\,0++$	ε_V^2	ε_V^0
$0\,0+-$	ε_V^0	ε_V^2
$0\,0\,0+$	ε_V^1	ε_V^1
$0\,0\,0\,0$	ε_V^0	ε_V^0

$$\epsilon_V = m_V/\sqrt{s}$$

Azatov, Contino, Machado, Riva 1607.05236

$0 = V_L, \phi$

$+, - = V_T$

$+½, -½ = \psi$

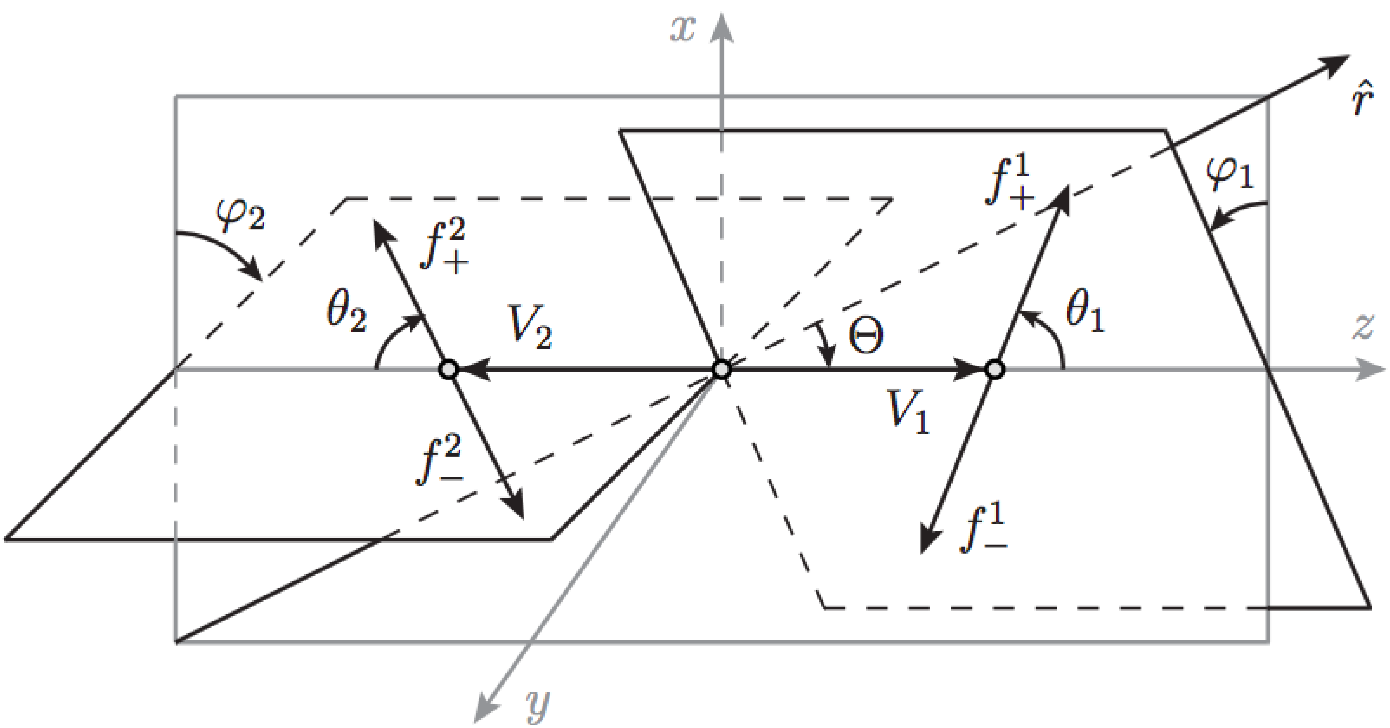
e.g. in W_TW_T and W_TW_L production, interference between SM and EFT does not grow with *s* Baglio, Dawson, Lewis 1708.03332

Restoring interference (1) – using decays

Correlations between decay products of gauge bosons

Use azimuthal angles to disentangle full 2 → 4

Intermediate particles with different helicities interfere



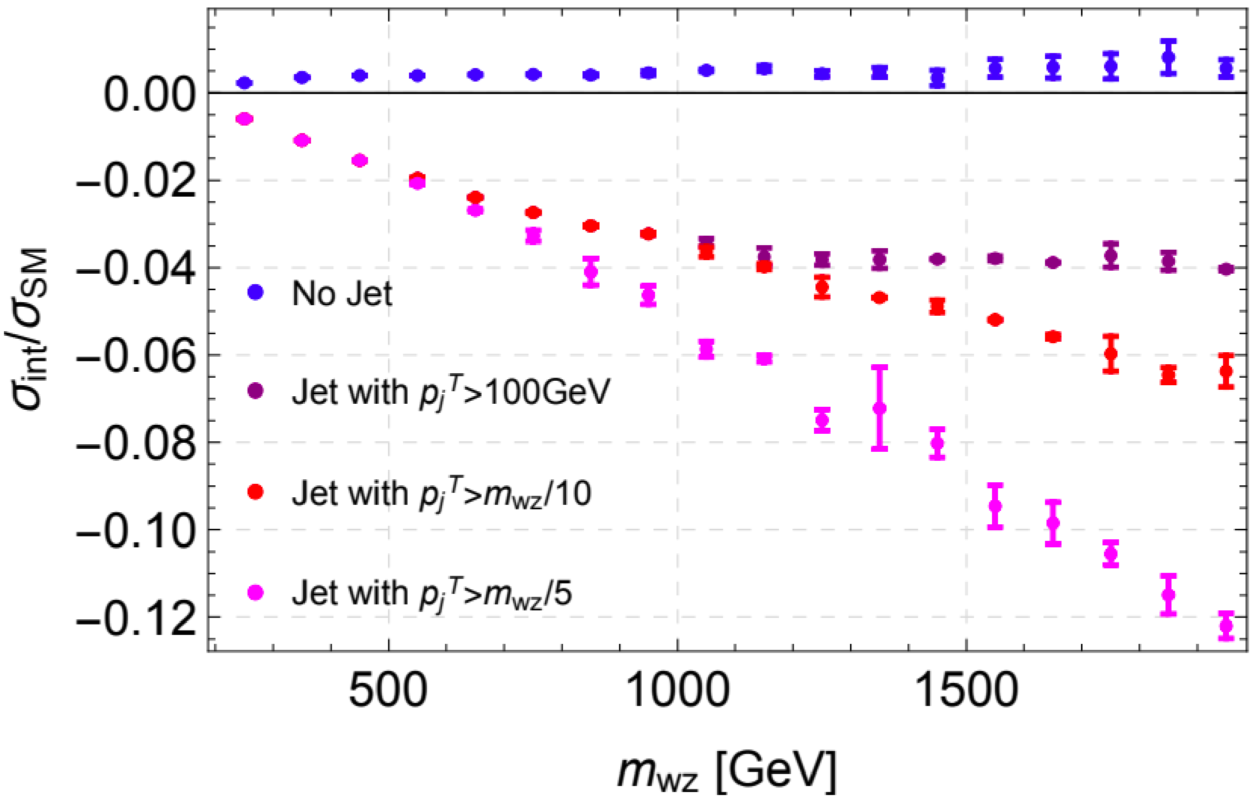
Panico, Riva, Wulzer
1708.07823

Restoring interference (2) – higher order

Go beyond LO

Originally used to probe G^3 operator in 3-jet events

Dixon and Shadmi hep-ph/9312363



Adding extra jet to gauge boson production

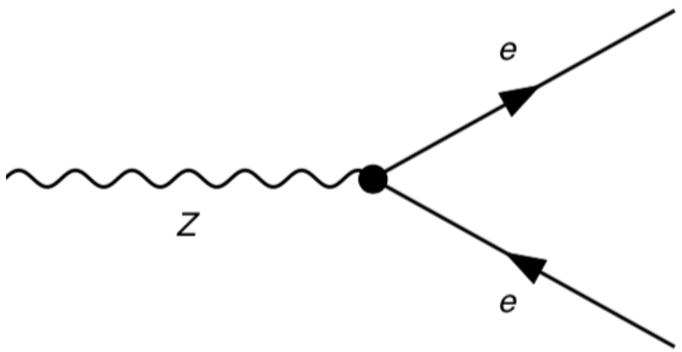
Azatov, Elias-Miro, Reyimuaji, Venturini 1707.08060

W^3 in Z decay at NLO

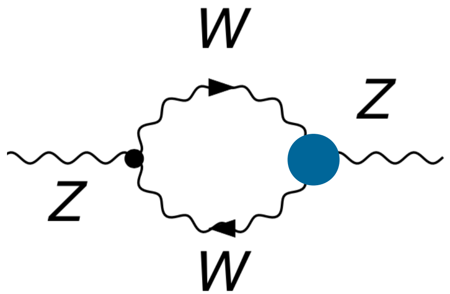
Suppressed interference in
q q → W W

No tree level contribution,
but appears at one loop

$$\mathcal{O}_W = \epsilon_{abc} W_\mu^{\nu a} W_\nu^{\rho b} W_\rho^{\mu c}$$

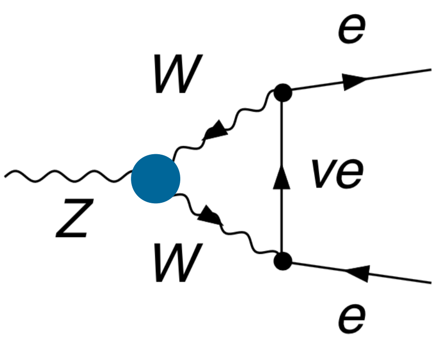


Z 2-point function



also: Z-photon mixing

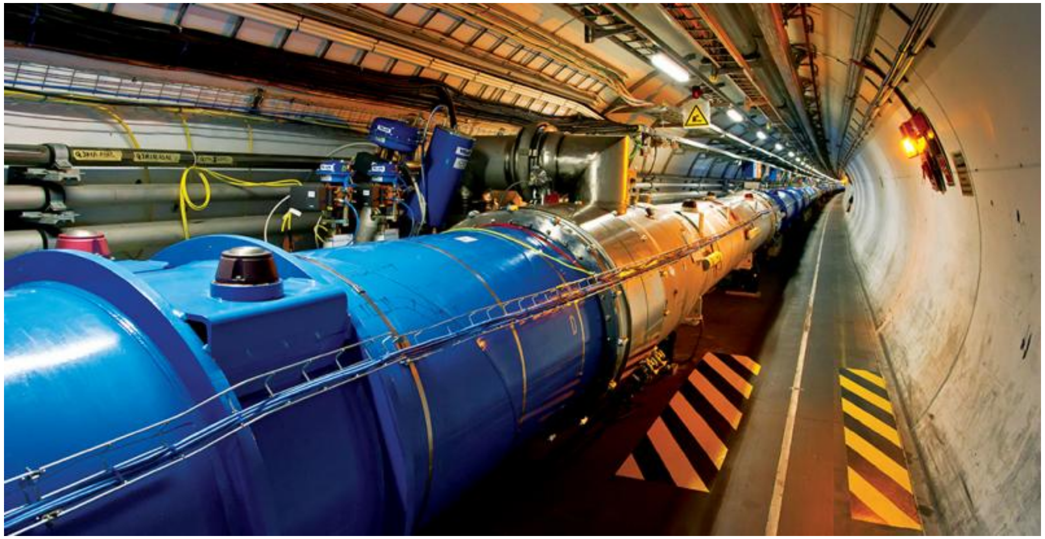
loop correction



Z bosons at high luminosity

2×10^{7} Z bosons recorded at LEP, all experiments and decays

HL-LHC: 5×10^{9} leptonic Z events per detector



Opportunity to probe subtle new physics effects, rare decays

NLO Z decay in SMEFT

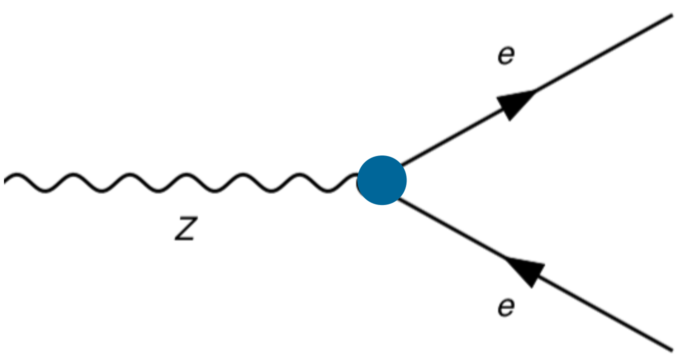
Keep only HWB and W[3] operators for simplicity

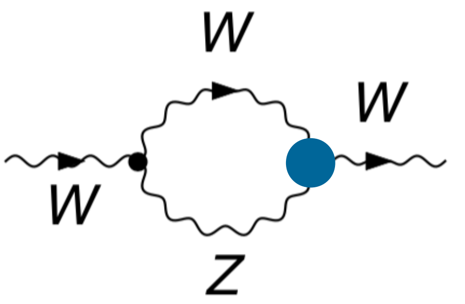
$$\mathcal{O}_{HWB} = H^\dagger \sigma^a H W^a_{\mu\nu} B^{\mu\nu}$$

$$\mathcal{O}_W = \epsilon_{abc} W_\mu^{\nu a} W_\nu^{\rho b} W_\rho^{\mu c}$$

Input parameters G_F, M_W, M_Z, M_H, M_t

W 2-point function



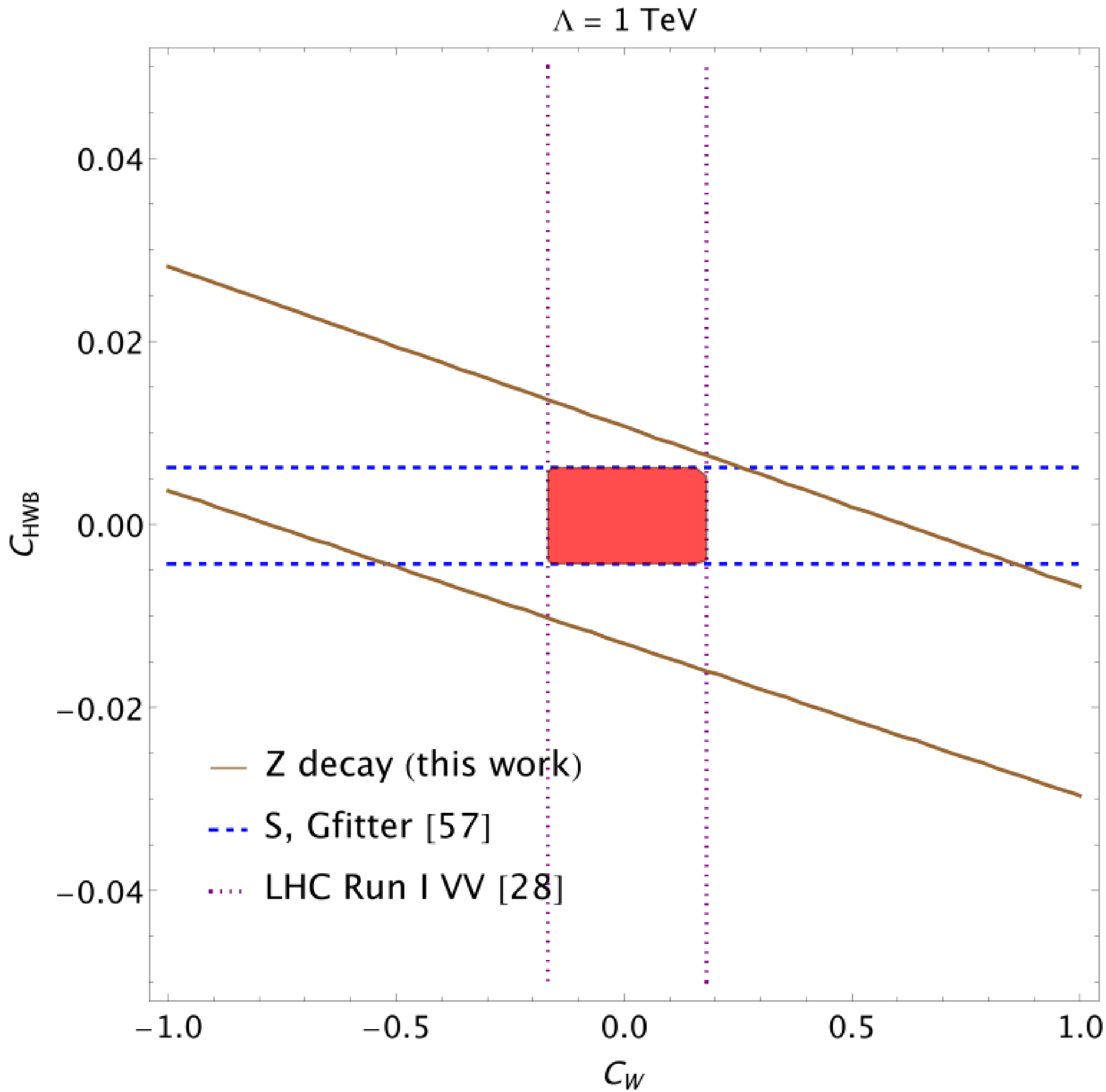


affects input parameter M_W

HWB operator gets contribution from W^3 operator at one loop

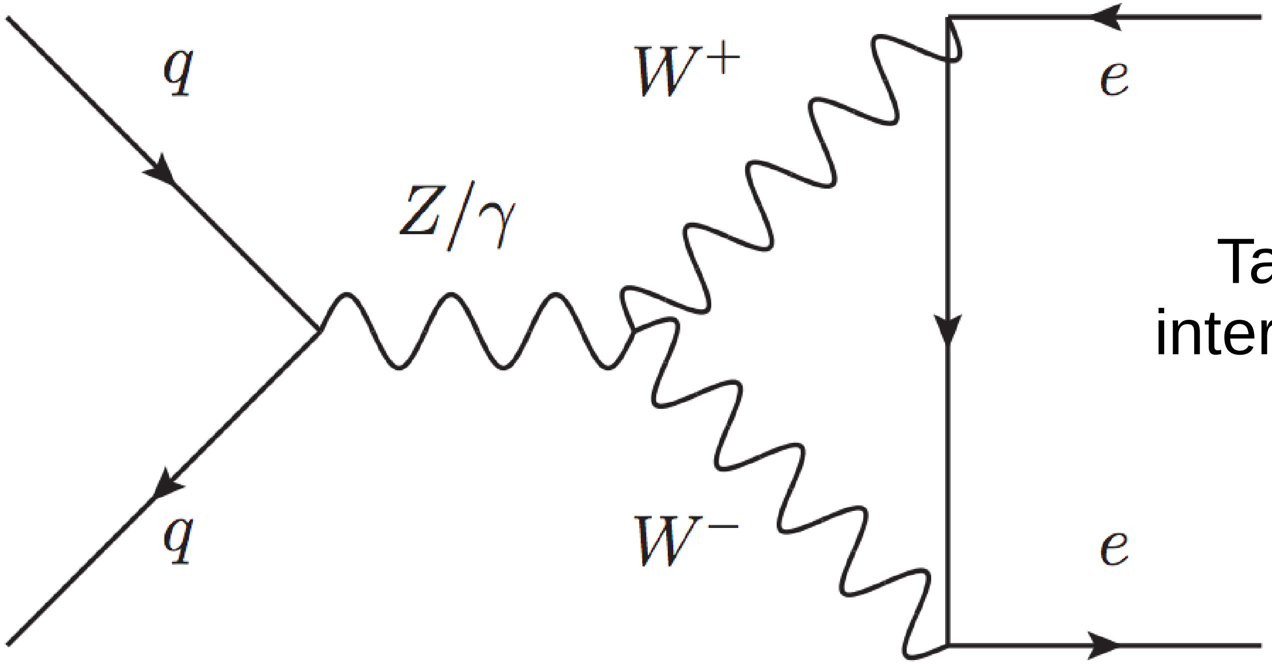
Renormalize with MS-bar scheme for EFT operators, on shell scheme for SM parameters

Z decay limits complementary to gauge boson production, despite being only a loop effect



NLO for Drell-Yan

Gauge boson operators at one loop also affect q q → ℓ ℓ, ℓ ν



Take advantage of interference increasing with energy

see also Farina et al., 1609.08157

SMEFT operators for Drell-Yan

– Four-fermion interactions

– Bosonic operators contributing at tree/loop level, including those affecting input parameters G_F, M_W, M_Z

$\mathcal{O}_W$	$\epsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$\mathcal{O}_{\phi D}$	$\left(\phi^\dagger D^\mu \phi\right)^* \left(\phi^\dagger D_\mu \phi\right)$	$\mathcal{O}_{\phi WB}$	$\left(\phi^\dagger \tau^I \phi\right)^* W_{\mu\nu}^I B^{\mu\nu}$
$\underset{p,r}{\mathcal{O}_{\phi l}^{(3)}}$	$(\phi^\dagger i \overleftrightarrow{D}_\mu^I \phi)(\bar{l}'_p \tau^I \gamma^\mu l'_r)$	$\underset{p,r,s,t}{\mathcal{O}_{lq}^{(1)}}$	$(\bar{l}'_p \gamma_\mu l'_r)(\bar{q}'_s \gamma^\mu q'_t)$	$\underset{p,r,s,t}{\mathcal{O}_{lq}^{(3)}}$	$(\bar{l}'_p \gamma_\mu \tau^I l'_r)(\bar{q}'_s \gamma^\mu \tau^I q'_t)$
$\underset{p,r,s,t}{\mathcal{O}_{qe}}$	$(\bar{q}'_p \gamma_\mu q'_r)(\bar{e}'_s \gamma^\mu e'_t)$	$\underset{p,r,s,t}{\mathcal{O}_{eu}}$	$(\bar{e}'_p \gamma_\mu e'_r)(\bar{u}'_s \gamma^\mu u'_t)$	$\underset{p,r,s,t}{\mathcal{O}_{ed}}$	$(\bar{e}'_p \gamma_\mu e'_r)(\bar{d}'_s \gamma^\mu d'_t)$
$\underset{p,r,s,t}{\mathcal{O}_{lu}}$	$(\bar{l}'_p \gamma_\mu l'_r)(\bar{u}'_s \gamma^\mu u'_t)$	$\underset{p,r}{\mathcal{O}_{ld}}$	$(\bar{l}'_p \gamma_\mu l'_r)(\bar{d}'_s \gamma^\mu d'_t)$	$\underset{p,r,s,t}{\mathcal{O}_{ll}}$	$(\bar{l}'_p \gamma_\mu l'_r)(\bar{l}'_s \gamma^\mu l'_t)$

Effect of loop interactions

W^3 operator contributes at loop level

Influence grows with energy

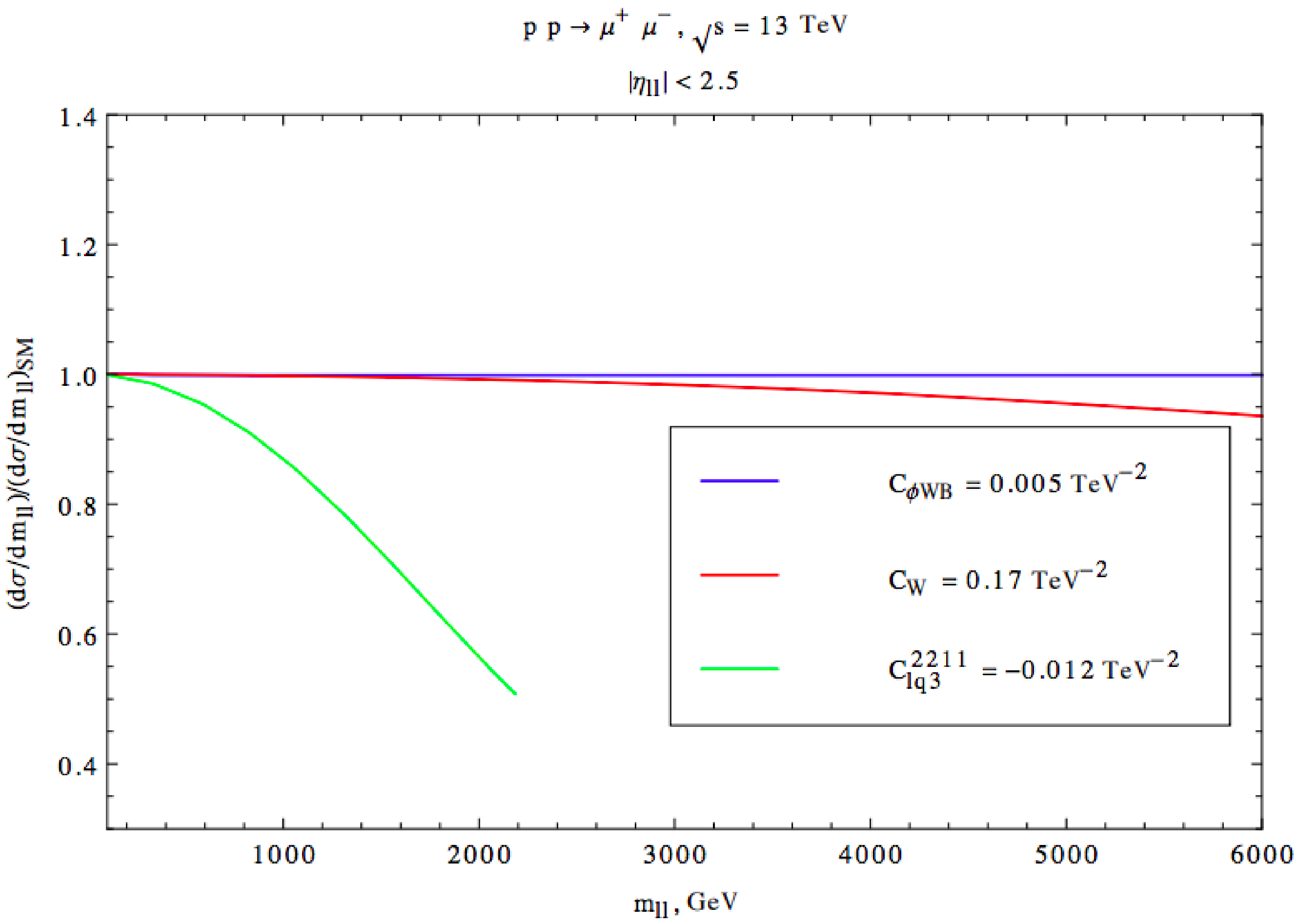
Restoration of interference

$$A_{LL,u}^{NLO} = A_{LL,u}^{SMEFT}\left(1 - \left[\frac{3sv^2}{\Lambda^2 M_Z^2(1+2c_W^2)}\right]\left\{\frac{g^3\mathcal{C}_W}{32\pi^2}\right\}\right)$$
$$A_{LL,d}^{NLO} = A_{LL,d}^{SMEFT}\left(1 + \left[\frac{3sv^2}{\Lambda^2 M_Z^2(1-4c_W^2)}\right]\left\{\frac{g^3\mathcal{C}_W}{32\pi^2}\right\}\right)$$

Kinematic distributions

Effect of W^3 operator subdominant compared to 4-fermion operator, yet visible at high energies

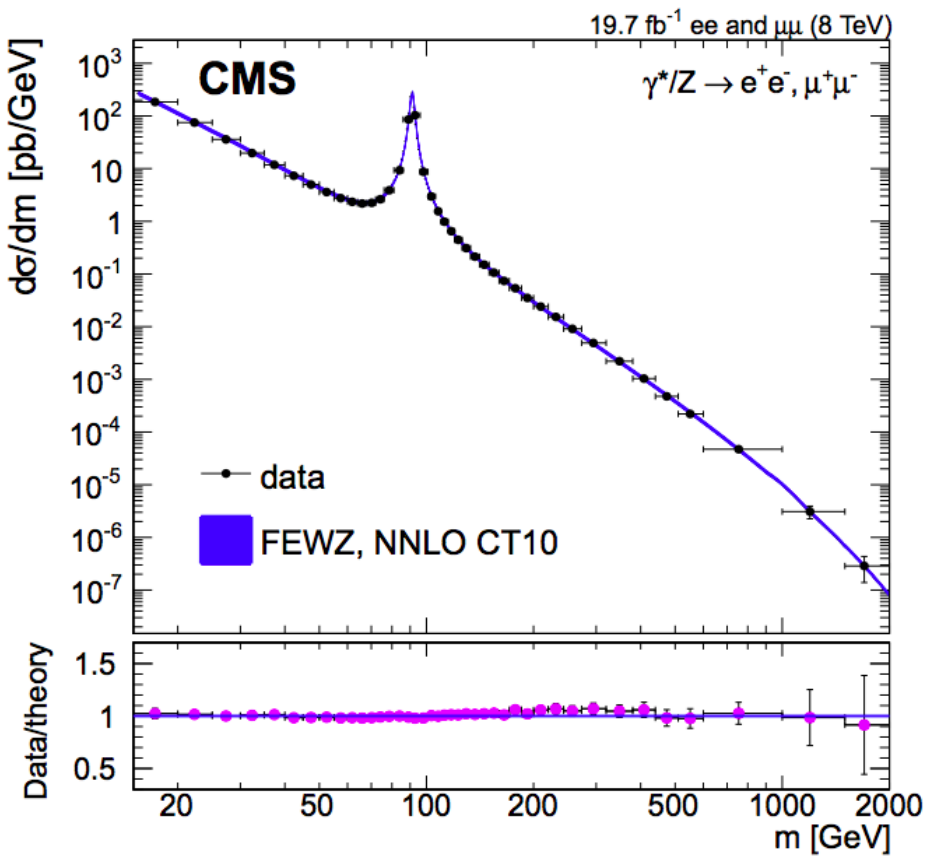
(operator sizes taken at current limits)

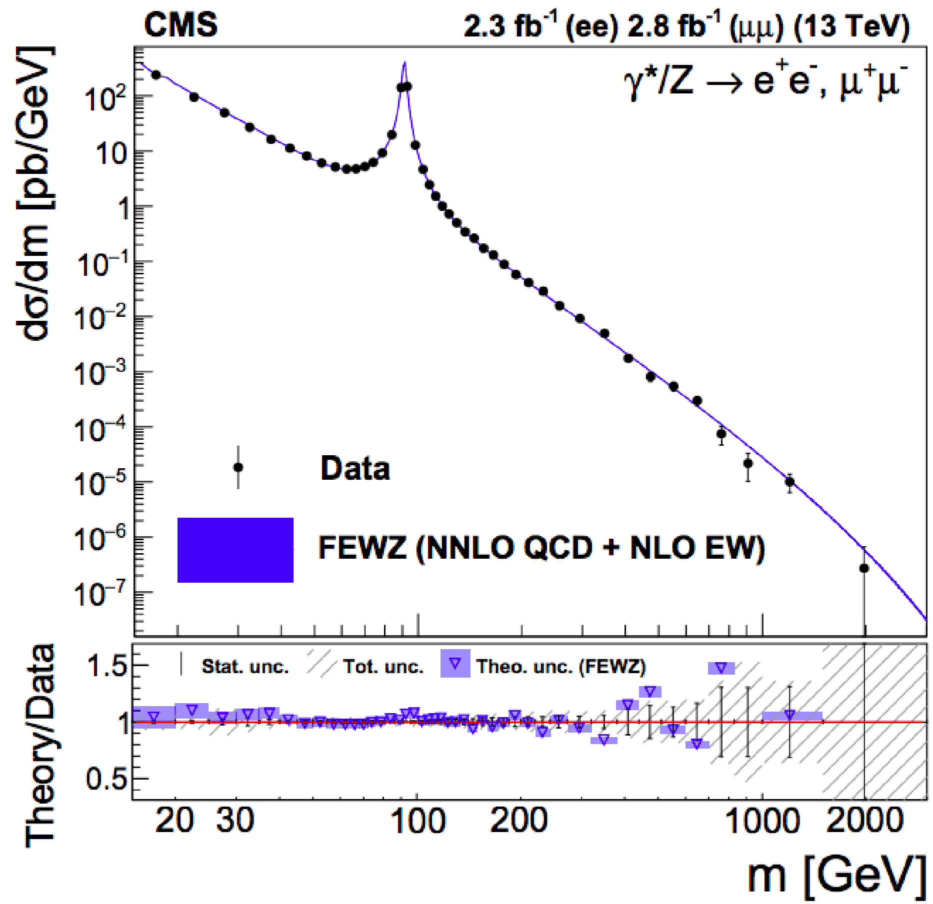


Predicting eventual reach

8 TeV measurements in high energy bins dominated by statistical uncertainties

Goes up to 2 TeV in invariant mass

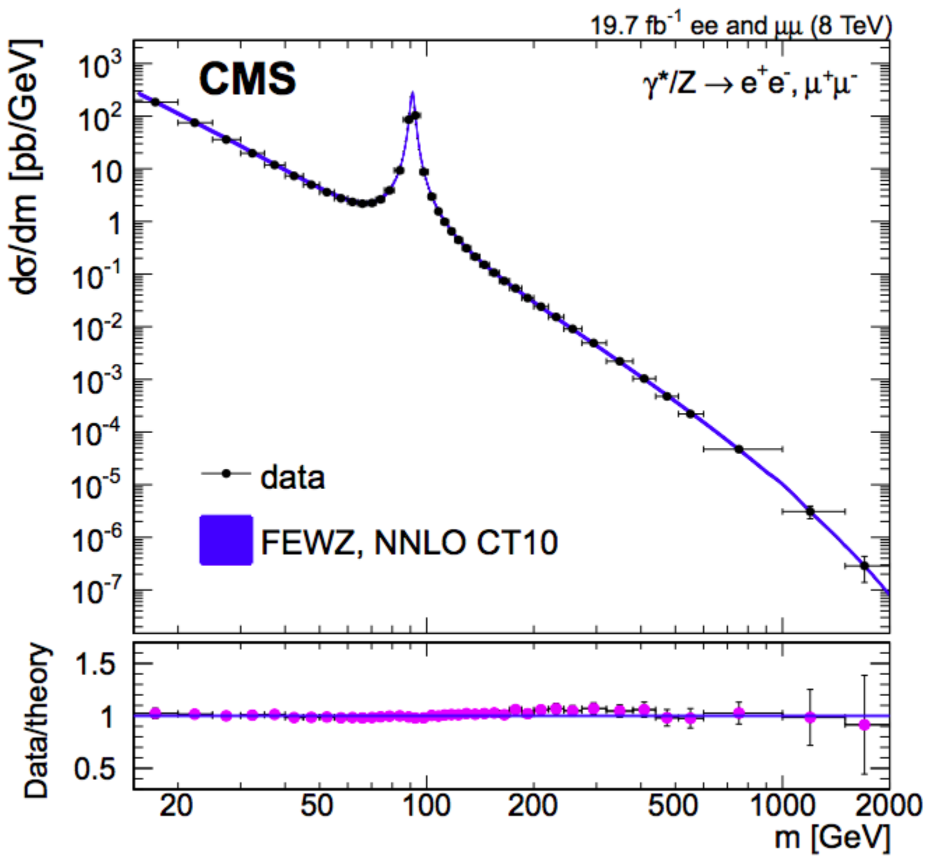


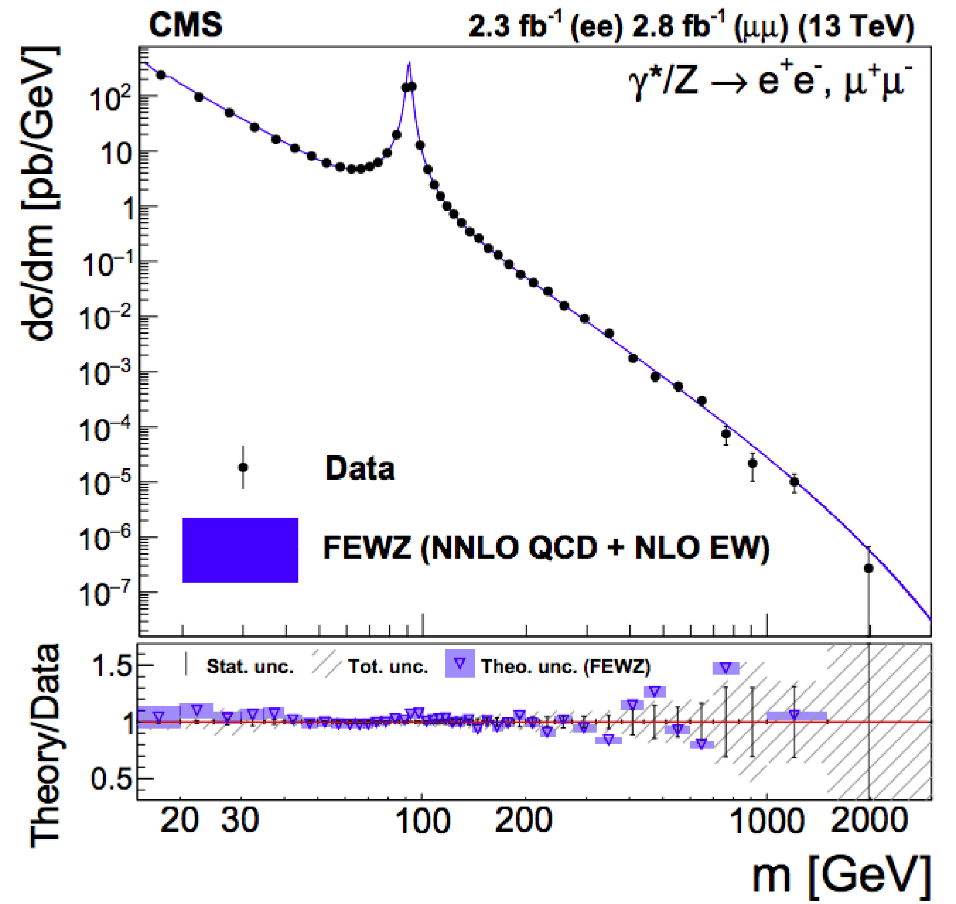


Predicting eventual reach

13 TeV currently goes up to 3 TeV dilepton mass

Maximal sensitivity limited by systematics in high energy bins, roughly 5%





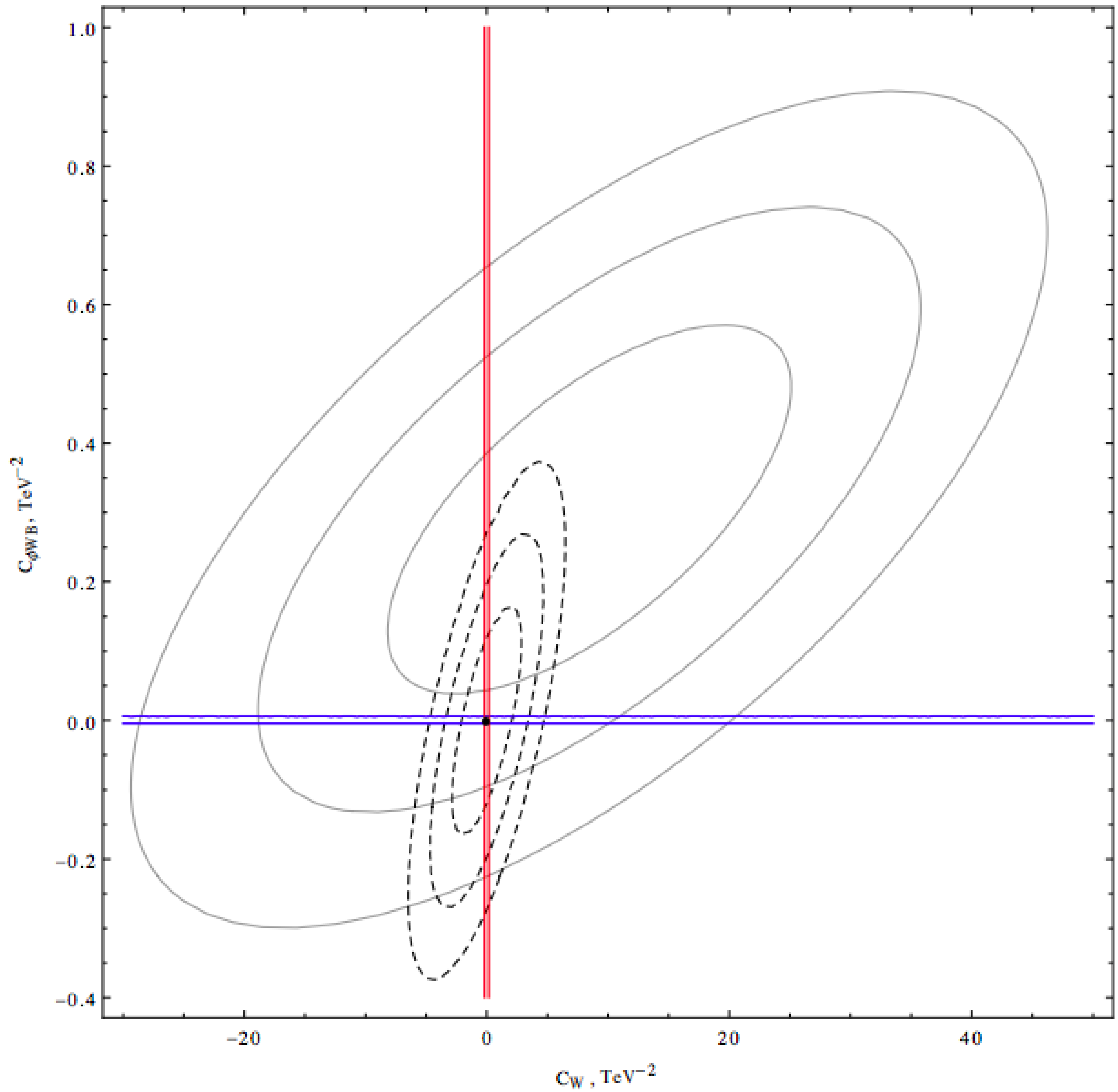
Predicting eventual reach

Solid: 8 TeV

Dashed: 13 TeV projection

Blue: S parameter from Gfitter

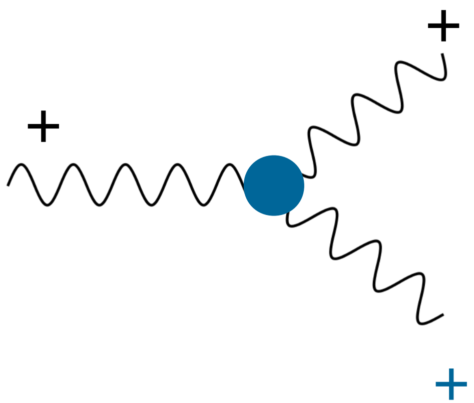
Red: VV production

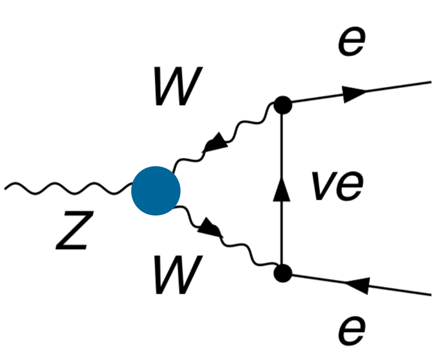


Summary

Loop effects of SMEFT important for eventual NLO global fit

Especially useful when interference between SM and EFT operators is suppressed





Z decay: complementary bounds on operators that only contribute at loop level

Drell-Yan: access NLO effects as well as gain from high energy